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Development of phase change materials based microencapsulated technology for buildings: A review

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ABSTRACT

Thermal energy storage (TES) systems using phase change material (PCM) have been recognized as one of the most advanced energy technologies in enhancing the energy efficiency and sustainability of buildings. Now the research is focus on suitable method to incorporate PCMs with building. There are several methods to use phase change materials (PCMs) in thermal energy storage (TES) for different applications. Microencapsulation is one of the well known and advanced technologies for better utilization of PCMs with building parts, such as, wall, roof and floor besides, within the building materials. Phase change materials based microencapsulation for latent heat thermal storage (LHTS) systems for building application offers a challenging option to be employed as effective thermal energy storage and a retrieval device. Since the particular interest in using microencapsulation PCMs for concrete and wall/wallboards, the specific research efforts on both subjects are reviewed separately. This paper presents an overview of the previous research work on microencapsulation technology for thermal energy storage incorporating the phase change materials (PCMs) in the building applications, along with few useful conclusive remarks concluded from the available literature.

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Contents

1. Introduction

The fast economic development worldwide leads to a quickly increasing energy demand. However, conventional fossil energy sources are limited, and their use is related to emission of harmful gases, which are responsible for climate changes and environmental pollution. Nowadays, thermal energy storage systems are essential for reducing dependency on the fossil fuels and then contributing to a more efficient environmental friendly energy use. As the demand for thermal comfort of buildings rises increasingly, the energy consumption is also increasing correspondingly in both the domestic and the commercial buildings. The building sector along with the industrial sector has become the dominant energy consumer around the world with a total 28% share of the overall energy consumption [1]. To cope-up with this challenging situation, energy resources need to be used more efficiently. Thus, improving energy efficiency of buildings is an effective means to improve the total energy efficiency of a society and has a significant benefit for the economy. Thermal energy storage can be accomplished either using sensible heat storage and/or using the latent heat storage. Sensible heat storage has been used for centuries by builders to store and release thermal energy passively, but a larger volume of material is

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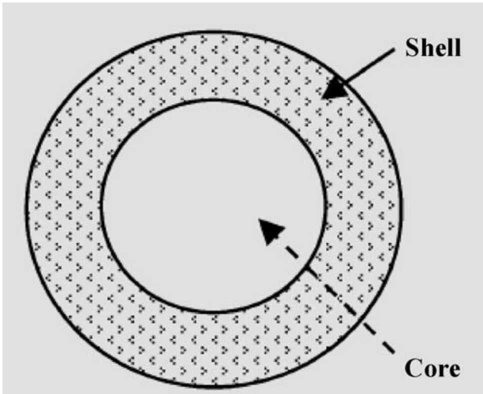

Fig. 1. Description of microcapsule.

required to store the same amount of energy in comparison to the latent heat storage material.

The principle of using the phase change materials is simple, as the heat supplies, the material changes its phase from solid to liquid and vice versa at constant temperature until it completely converts into solid. Similarly, when heat is released, the material changes phase from liquid to solid. Again at constant temperature until it solidifies completely [2]. The buildings with a traditional structure have a large thermal inertia (sensible heat storage) and supply natural air conditioning in the rooms. In the commercial sector, the trend is to decrease the wall thickness to reduce the weight, material consumed, the transport costs and the construction time. The latent heat storage by incorporating a phase change material (PCM) into some building materials is an attractive way to compensate for the small storage capacity of most existing modern buildings as well as next generation. The main disadvantage of light weight buildings is the low thermal mass tending to the large temperature fluctuations due to external heating or cooling load. Using PCM material in such buildings can decrease the temperature fluctuation, particularly due to incident solar radiations loads as proved in several numerical studies [3,4].

Nowadays, microencapsulation technology is the prominent for use of PCM in building materials. With the advent of PCM implemented in gypsum board, plaster, concrete and/or other wall covering materials, thermal storage can be part of the building structure even for light weight buildings. Several forms of bulk encapsulated PCMs have been developed for active and passive solar applications in building including direct heat gain. However, the surface area of most encapsulated commercial products has been inadequate to deliver heat to the building after the PCM melted by direct solar radiation [5]. One problem to solve in some PCM applications is the liquid migration, using some kinds of packing. Microcapsules consist of little containers, which pack a core material with a hard shell. Microencapsulating PCM brings some more important advantages like that microcapsules can handle phase change materials as core, as far as, they tolerate volume changes.

2. Microencapsulation

It is the process by which individual particles or droplets of solid or liquid material (the core) are surrounded or coated with a continuous film of polymeric material (the shell) to produce capsules in the micrometer to millimeter range, known as microcapsules (Fig. 1). Microcapsules may be spherically shaped, with a continuous wall surrounding the core, while others are asymmetrically and variably shaped, with a quantity of smaller droplets of core material embedded throughout the microcapsule. All three states of matter (solids, liquids, and gases) may be microencapsulated. This allows liquid and gas phase materials to be handled more easily as solids, and can afford some measure of protection in handling hazardous materials.

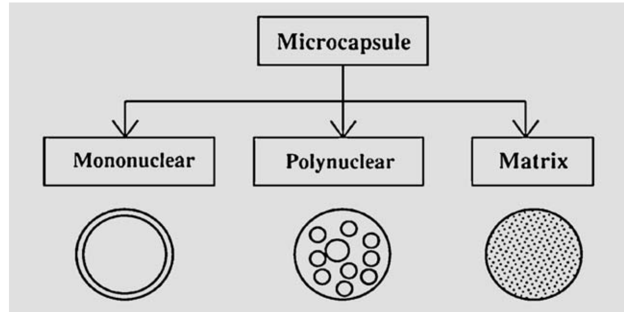

Fig. 2. Type of microcapsule.

Microencapsulation may be achieved by a myriad of techniques, with several purposes in mind. Microcapsules are tiny little containers which pack the core material individually with a hard shell. Microcapsules can therefore handle even liquids as solid material. They tolerate phase changes including volume changes in their core and can handle phase change materials as core. Microcapsules may be processed as aqueous dispersion or powder and improve the formulation of phase change materials as many building materials go through a powder state during processing. Phase change temperatures between −10 and 80 °C are possible to manufacture with microcapsules [6]. Several physical and chemical methods have been developed for production of microcapsules [7]. The most often used microencapsulation methods are:

Physical methods:

(i) pan coating,
(ii) air-suspension coating,
(iii) centrifugal extrusion,
(iv) vibrational Nozzle,
(v) spray drying.

Chemical methods:

(i) interfacial polymerization,
(ii) in situ polymerization,
(iii) matrix polymerization.

The description of microcapsules depends mainly on the core material and the deposition process of the shell (Fig. 2).

1. Mononuclear (core–shell) microcapsules contain the shell around the core.
2. Polynuclear capsules have many cores enclosed within the shell.
3. Matrix encapsulation in which the core material is distributed homogeneously into the shell material.

3. Phase change materials for microencapsulation

Potential phase change materials (PCMs) that can be applied in buildings depend on suitable temperature range (between 18 and 28 °C) in the range of human comfort temperature. Some selected PCMs for microencapsulation having good potential are given in Table 1. It is well known that the inorganic PCMs, typically hydrated salts, have some attractive properties such as, a higher energy storage density, a higher thermal conductivity, being non-flammable, being inexpensive and readily available. However, they also have some obvious disadvantages such as being

Table 1
PCMs investigated in the literature for microencapsulated with building materials.

PCM	Transition point/range (°C)	Heat of fusion (kJ/kg)	References
$CaCl_2 \cdot 6H_2O$	24–29	192	[48,49]
$CaCl_2 \cdot 6H_2O$ + Nucleator + $MgCl_2 \cdot 6H_2O$ (2:1)	23	–	[50]
Hexadecane	18	236	[51]
	18	205	[52–55]
Heptadecane	18	214	[51]
Octadecane	22	244	[51]
Black paraffin	25–30	150	[51]
Emerest 2325 (butyl stearate + butyl palmitate 49/48)	17–21	138–140	[56,57]
Emerest2326 (butyl stearate + butyl Palmitate 50/48)	18–22	140	[58,59]
Butyl stearate	19	140	[8,60]
1-Dodecanol	26	200	[8]
Capric–lauric 45/55	21	143	[8]
Capric–lauric 82/18	19.1–20.4	147	[61]
Capric–lauric 61.5/38.5	19.1	132	[62,63]
Capric–myrstic 73.5/26.5	21.4	152	[62,63]
Capric–palmitate 75.2/24.8	22.1	153	[62,63]
Capric–stearate 86.6/13.4	26.8	160	[62,63]
Peg1000 + Peg600	23–26	150.5	[64]
Propyl palmitate	19	186	[59]
RT25		147	[65]

corrosive, being incompatible with some building materials and required suitable supporting containers. In particular, they experience super-cooling and phase segregation during transition and their application requires the use of some nucleating and thickening agents.

In recent years, some organic PCMs are getting more and more attention due to the avoidance of the problems inherent with inorganic PCMs. They have little super-cooling and phase segregation, and are compatible with and suitable for absorption in various building materials [8]. However, they are flammable and have volume changes and low heat conductivity as mentioned in many recent studies [9]. Eutectic or non-eutectic mixtures of organic or inorganic PCMs could be used to deliver the desired melting point required [10]. Fan et al. [11] worked on super-cooling prevention of microencapsulated phase change materials. The microcapsules comprising *n*-octadecane and nucleating agents encapsulated in melamine–formaldehyde resin shell with about 1 μm in average diameter, prepared through in situ polymerization [12–14].

The effects of nucleating agents, i.e. sodium chloride, 1-octadecnol (Fig. 3(a) and (b)) and paraffin (Fig. 4(a) and (b)), on the crystallization properties, morphology and dispersibility of microcapsules were investigated using SEM, DSC (differential scanning calorimetry). The super-cooling was prevented by adding about 6 wt.% sodium chloride to the emulsion, however, the microcapsules were worse dispersed and their surfaces were rough. Adding approximately 9 wt.% 1-octadecanol in core material was found to prevent microcapsules from super-cooling, but the microcapsules were easily conglomerated and their surfaces were extraordinarily rough. Microcapsules with approximately 20 wt.% paraffin in core material were free from super-cooling, and paraffin had no influence on the morphology and dispersibility of microcapsules. Zhang [15] focused on microencapsulated *n*-octadecane with polyurea shells containing different soft segments for heat energy storage and thermal regulation. In this work he microencapsulated *n*-octadecane with polyurea shells containing different soft segments by synthesizing using 2,4-tolylene diisocyanate as an oil-soluble monomer and various amines as a water-soluble monomer through interfacial polycondensation (Fig. 5). The Fourier transform infrared spectra and optical phase contrast microscope confirmed that these polyurea shell materials were successfully fabricated onto the surface of *n*-octadecane. The morphological investigation suggested that the microcapsules synthesized using Jeffamine as the amine monomer had a smoother and more compact surface than those synthesized by ethylene diamine and diethylene triamine, and they possessed a larger particle size (about 16 mm) with a centralized size distribution as well. These microcapsules also exhibited much

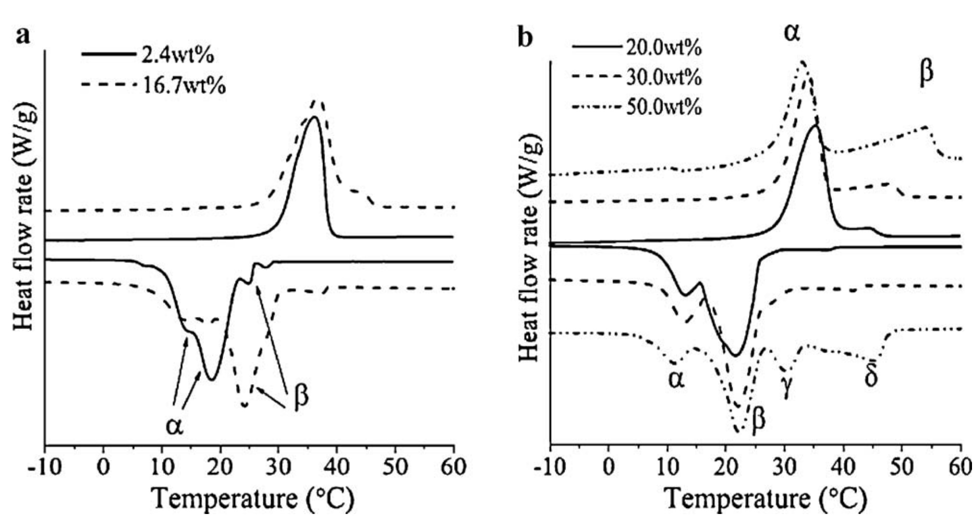

Fig. 3. (a) DSC curves of Micro-PCMs with 1-octadecanol of various concentrations in core material. (b) DSC curves of Micro-PCMs with paraffin of various concentrations in core material.

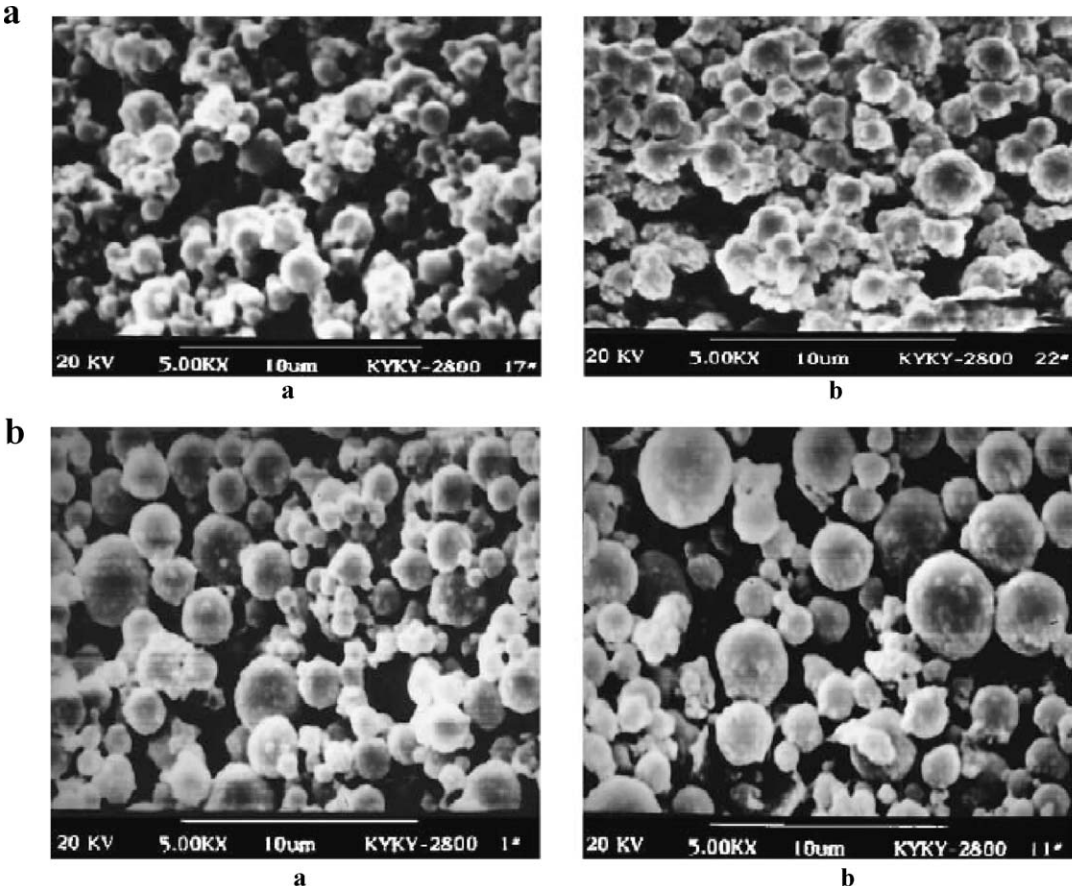

Fig. 4. (a) SEM photographs of microcapsules with 1-octadecanol of various concentrations in core material. (a) 2.4 wt.%, (b) 9.1 wt.%. (b) SEM photographs of microcapsules with paraffin of various concentrations in core material. (a) 20.0 wt.%, (b) 50.0 wt.%.

better phase change properties, higher encapsulation efficiency, and better anti-osmosis property than the other two. In addition, the microcapsules synthesized with a core/shell weight ratio of 70/30 are optimal when used as microencapsulated phase change materials.

Onder et al. [16] were also encapsulated three types of paraffin waxes, namely *n*-hexadecane, *n*-octadecane and *n*-nonadecane. The complex coacervation method has been used in this study succeeded to encapsulate paraffin waxes of high heat storage capacities by means of natural and biodegradable polymers, namely gelatin and gum arabic. The coacervates, manufactured for *n*-hexadecane and *n*-octadecane, each included by low, medium and high percentages and *n*-nonadecane included by medium percentage, have performed their functions of energy absorption perfectly during their heating at different rates, say 0.5–1 and $10\,^{\circ}\mathrm{C\,min^{-1}}$ in calorimeter and DSC tests. The achieved enthalpies were found proportional to those of hydrocarbons in temperature intervals corresponding to the phase transitions of PCMs. FTIR results were also presented the proofs of successful complex coacervation of PCMs.

Sarier and Onder [17] worked on the thermal insulation capability of PEG-containing polyurethane foams. Polyethylene glycol (PEG) compounds and mixtures have many properties that make them suitable for thermal applications in buildings, such as having high heat of fusion, phase change repeatability, chemical stability, non-corrosive behavior, and low-cost. They tested a new approach to integrate PEGs as PCM in insulation materials of foam type. Three different types of PEGs were used so that the different melting temperature ranges were possible for those developed materials. DSC analyses of PU-PEG composites yielded high enthalpies in certain temperature intervals indicating that the heat absorption/release capacities of PU foams could be improved by means of PEG incorporation. Thermal analyses of the new materials also proved that the contained PCMs are active. The PU-PEG composites produced here can be helpful for the design of thermal insulators. Furthermore, PU foams containing PEGs can be assumed to be leak-resistant, which is promising for their industrial applications.

Sarı et al. [18] studied the microencapsulated *n*-octacosane as phase change material for thermal energy storage. This study deals with preparation and characterization of polymethylmetracrylate (PMMA) microcapsules containing *n*-octacosane as phase change material. The surface morphology, particle size and particle size distribution (PSD) were studied by scanning electron microscopy (SEM) (Fig. 6(a)). The chemical characterization of PMMA/octacosane microcapsules was made by FT-IR spectroscopy method. Thermal properties and thermal stability of microencapsulated octacosane were determined using differential scanning calorimetry (DSC) (Fig. 6(b)) and thermal gravimetric analysis (TGA). The melting and freezing temperatures and the latent heats of the microencapsulated octacosane as PCM were measured as 50.6 and $53.2\,^{\circ}\mathrm{C}$, 86.4 and 88.5 J/g, respectively, using DSC analysis. TGA analysis indicated that the microencapsulated octacosane degrade in two steps and had good chemical stability. Thermal cycling test was also conducted and results indicated that PMMA/octacosane microcapsules are reliable according to the thermal cycling tests. In addition, the thermogravimetric investigation showed that the PMMA/octacosane microcapsules degrade in two steps and resistant to high temperatures. Based on all results, it

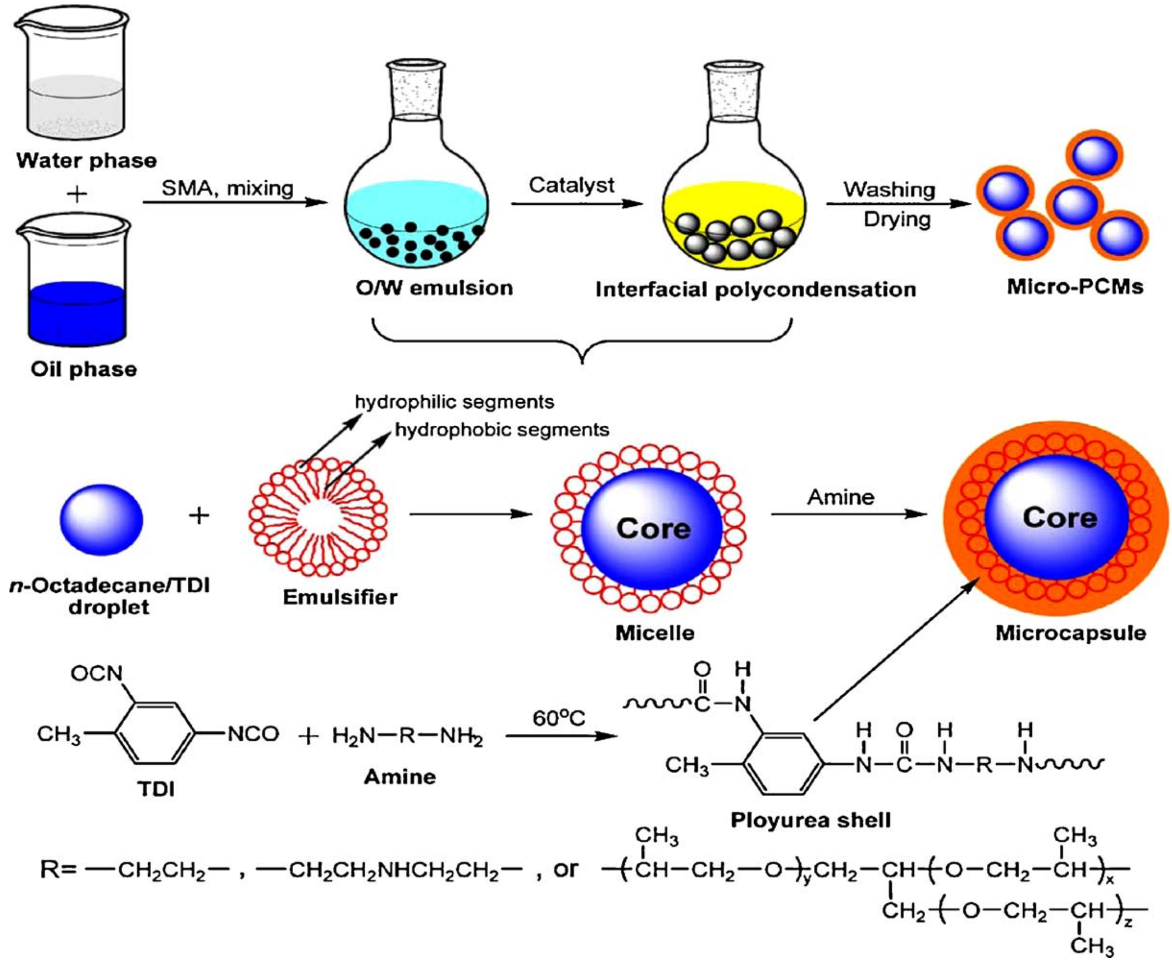

Fig. 5. Schematic formation of the microencapsulated *n*-octadecane with the polyurea shells containing different soft segments through interfacial polycondensation.

can be concluded that the prepared microencapsulated octacosane have good energy storage potential.

Zhang and Niu [19] presented the experimental investigation of effects of super-cooling on microencapsulated phase-change material (MPCM) slurry for thermal storage capacities. MPCM slurry has been made by microencapsulating phase change material with a thin film as shell and dispersing the microencapsulated PCM into an aqueous solution as a carrier fluid. Hexadecane ($C_{16}H_{34}$) was chosen as the core material, whose melting temperatureis18 °C, and latent heat is 234 kJ/kg, and amino plastics as shell material, respectively. The core–shell ratio was controlled to be about 7:1 by weight during the preparing process; the thickness of the shell was 0.3 μm. They experimentally investigated the melting and crystallization behaviors of MPCM slurry, by running in a thermal storage test system. Super-cooling and effective latent heat of MPCM slurry with different experimental conditions was also investigated. The experiment results show that, in a practical air conditioning system with thermal energy storage, the latent heat transition is not entirely complete. For the specific MPCM investigated, the utilization ratio of the latent heat is related to the end temperature, and is around 80% when cooled to around 8 °C.

Fang et al. [20] studied the nano-encapsulated *n*-tetradecane as phase change material for thermal energy storage. In situ polymerization method has been applied for preparation of nanocapsules as phase change material (PCM) using *n*-tetradecane as the core material, while urea and formaldehyde were used for the shell polymerization. Sodium dodecyl sulfate has been used as the emulsifier while resorcin was used as the system modifier. The morphology of the nanocapsules was observed by a scanning electronic microscope (SEM). The thermal properties were investigated by a differential scanning calorimeter (DSC) and a thermogravimetry analysis (TGA). The SEM analysis indicated that the nanocapsules had general size of about 100 nm and the core material was well encapsulated. DSC analysis indicated that the mass content of *n*-tetradecane was up to 60%, which resulted in a high latent heat of fusion of 134.16 kJ/kg. Thermogravimetry analysis (TGA) showed the thermal stability of the nanocapsules could be improved using the additives such as NaCl in the polymerization. The nanocapsules could be applied for thermal energy storage and heat transfer enhancement.

Taguchi et al. [21] attempted to prepare microcapsules by absorbing *n*-pentadecane as the phase change material (PCM) and methyl methacrylate (MMA) as the shell material into oil absorbable polymer particles. The effects of the volume of MMA absorbed and the soaking time on a few characteristics of the PCM microcapsules were investigated and the following results were obtained.

(i) Oil absorbable polymer particles absorbed *n*-pentadecane of nine times the weight of themselves.
(ii) The latent heat storage density for PCM microcapsules decreased from 107 to 97 kJ/kg according to the volume of MMA absorbed.
(iii) The phase change temperature for the PCM microcapsules decreased from 10 to 9.5 °C according to the volume of MMA absorbed.

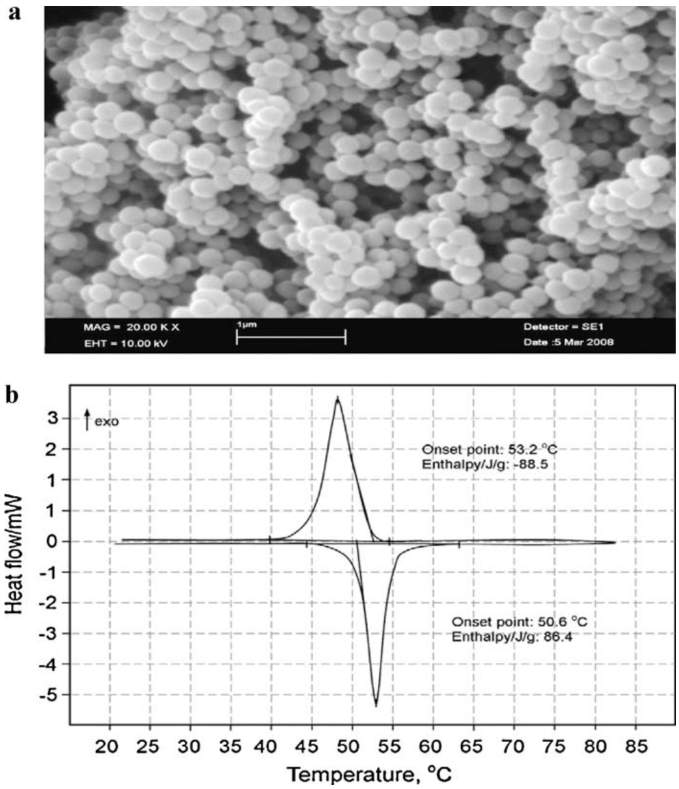

Fig. 6. (a) SEM image of PMMA/octacosane microcapsules. (b) DSC thermogram for PMMA/octacosane microcapsules.

(iv) The diameters of the PCM microcapsules increased from 650 to 760 μm with the volume of MMA absorbed.
(v) The destroyed rate was drastically decreased with increasing the volume of MMA absorbed and the soaking time.
(vi) The leakage of PCM from microcapsules was not observed at the conditions of $Wm = 5.0$ and $10\,cm^3$.

Sánchez et al. [22] developed a cheap and technically feasible process for the encapsulation of different phase change materials with a polymer shell of polystyrene by suspension polymerization. This method based on a suspension polymerization allows the encapsulation of non-polar PCMs, while that it was not possible to encapsulate the polar PCMs (polyglycols). Different PCMs such as paraffin wax, tetradecane, Rubitherm RT-27, Rubitherm-20, nonadecane can be encapsulated by this method to form a core–shell structure with the main emphasize on the preparation and characterization of encapsulated paraffin wax. Thermal properties, the morphology and the particle size distribution of the microcapsules obtained were determined by differential scanning calorimetry, scanning electron microscopy and laser diffraction. They [22] observed that the diameter, the melting heat and the amount of microcapsules obtained in each experiment vary with the PCMs used. Finally they conclude that the encapsulated paraffin wax could be considered to have good potential for energy storage.

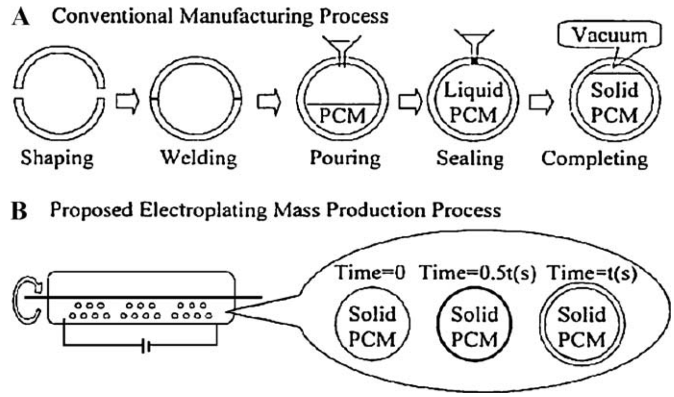

Fig. 7. Comparison between conventional and proposed processes for the PCM encapsulation.

Akiyama and co-workers [23,24] described a new fabrication method of encapsulation of phase change material (PCM) for storing and reusing high temperature waste heat from an industry. In the experiments (Fig. 7), lead pellets were selected as a PCM, then encapsulated by nickel film based on an electro-plating method and were tested by cyclic heating for practical use. At the same time, thermal stress model was developed, validated by the measured data and implemented to study the effect of the film thickness on the strength of capsules. The conclusions of the study are

(1) The PCMs obtained by electroplating had enough strength during melting-solidification cyclic processes, if the film is thick enough or the PCM diameter is small enough.

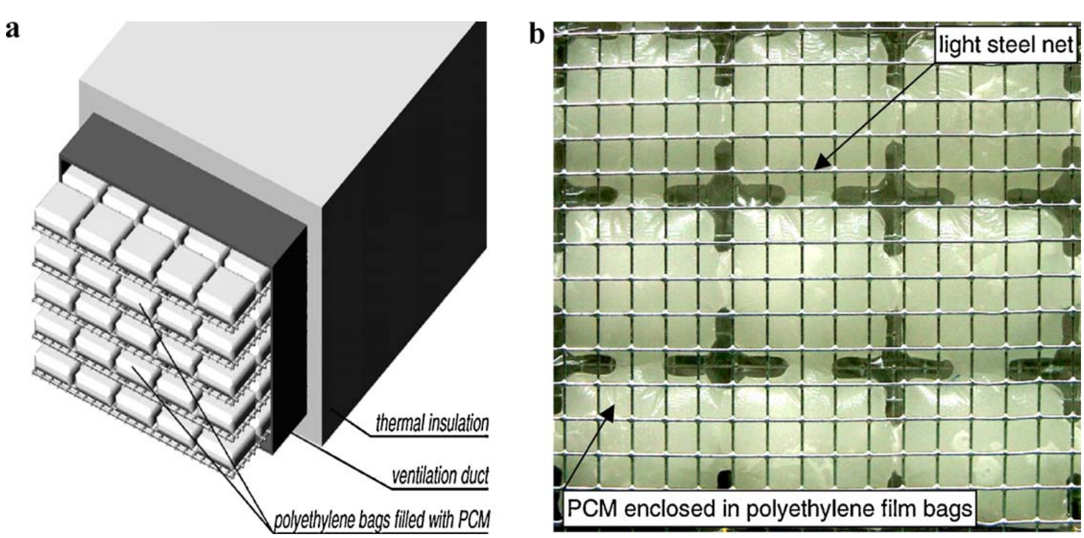

Fig. 8. (a) Schematic of the TES device under study. 8(b) Polyethylene film bags filled with PCM.

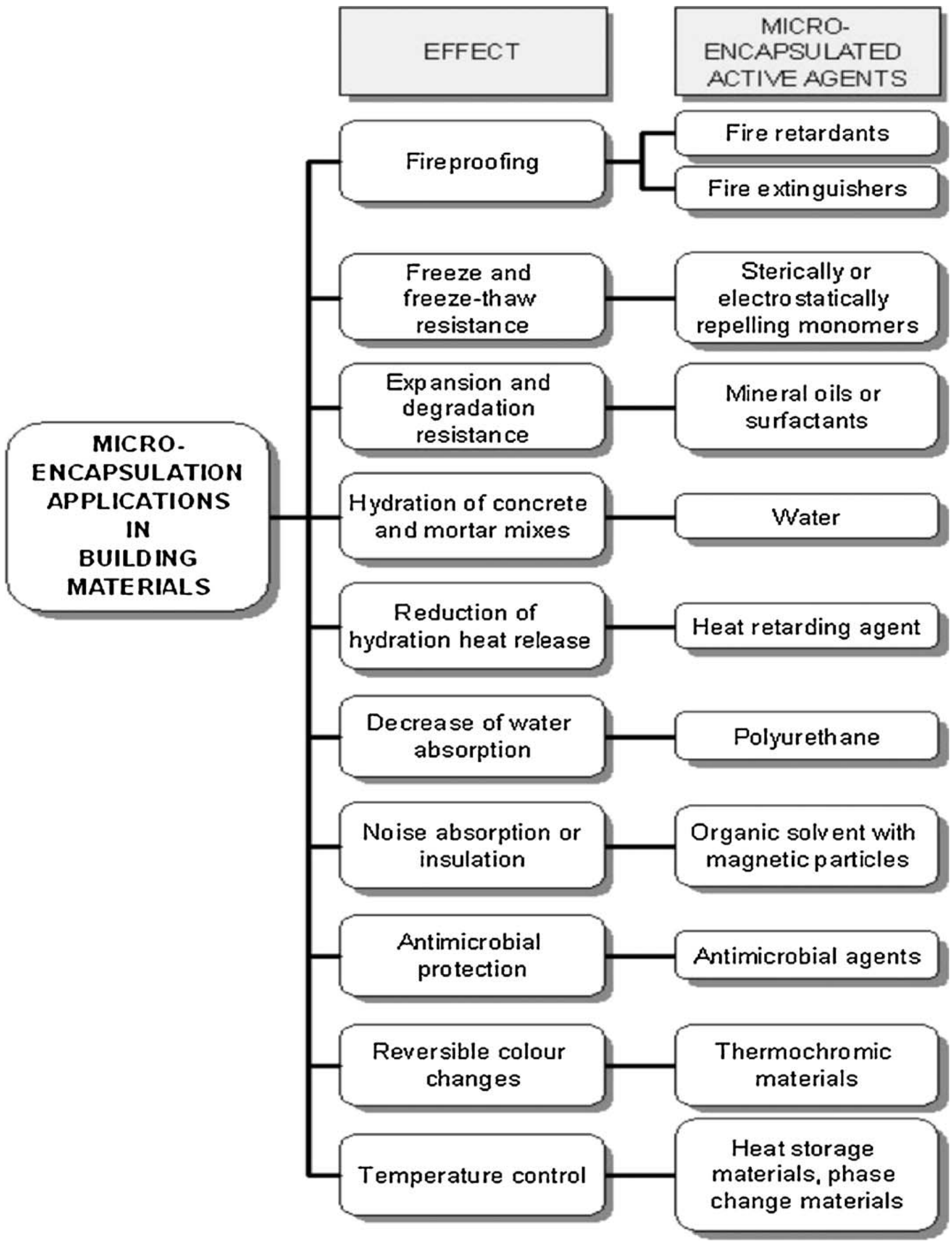

Fig. 9. Applications of microcapsules in building construction materials.

(2) This relation was well explained by the thermal stress model.
(3) The stress analysis and observation suggested that the coated film was not uniform and an inactive, weak layer existed. The stress model, modified by considering this inactive layer well predicted a critical value of tensile stress. This will be benefit for evaluating the required film thickness of various PCM pellets.

Zukowski [25] focused for short-term thermal energy storage (TES) unit based on an enclosed phase change material (PCM) in polyethylene film bag (Fig. 8(a) and (b)). As a storage medium, paraffin wax (RII-56) has been used to present the experiment results, including charge, discharge and pressure drop characteristics of the tested unit. The total enthalpy storage in the module depends on the PCM temperature change which ranges from 240 to 262 kJ/kg. The results of the investigations showed that paraffin wax RII-56 is a material that can be successfully used in TES applications in processes and buildings that requires energy to be stored for short term. There are more than 100 PCMs for different temperature ranges; some of the commercially available PCMs are given in Table 2.

4. Applications of microencapsulated PCMs in buildings

Most of the buildings in the developed world use conventional building materials: bricks and mortar, concrete (with or without steel reinforcement), or steel or wood framing for structural components, insulation to reduce space conditioning loads, and plaster or gypsum wallboard finishing indoors. Although insulation can

Table 2
Commercial PCM manufacturers companies in the world.

Manufacture	PCM temperature range (°C)	Number of PCMs listed	Reference
RUBITHERM (www.rubitherm.de)	−3 to 100	29	[66]
Cristopia (www.cristopia.com)	−33 to 27C	12	[67]
TEAP (www.teappcm.com)	−50 to 78	22	[68]
Doerken (www.doerken.de)	−22 to 28	2	[69]
Mitsubishi Chemical (www.mfc.co.jp)	9.5 to 118	6	[70]
Climator (www.climator.com)	−18 to 70	9	[71]
EPS Ltd (www.epsltd.co.uk)	−114 to 164	61	[72]

enable the different wall types to have similar insulating values (thermal conductivity), the thermal mass of walls, i.e. the quantity of heat it takes to increase or decrease the temperature, can vary greatly. For example, a concrete wall has much more thermal mass than a framed wood wall per unit volume. In buildings, thermal mass reduces temperature swings, which increases occupant comfort and can reduce cooling load and hence, Power consumption and peak cooling demands in some climates.

Analysis of scientific articles and patents shows numerous possibilities of adding microencapsulated active ingredients into construction materials, such as cement, lime, concrete, mortar, artificial marble, sealants, paints and other coatings. Summary of applications is presented in (Fig. 9). The new researches are going to increase the thermal mass of building structures by incorporating phase-change materials (PCMs) into building materials. The PCM incorporated in building walls are used to enhance the

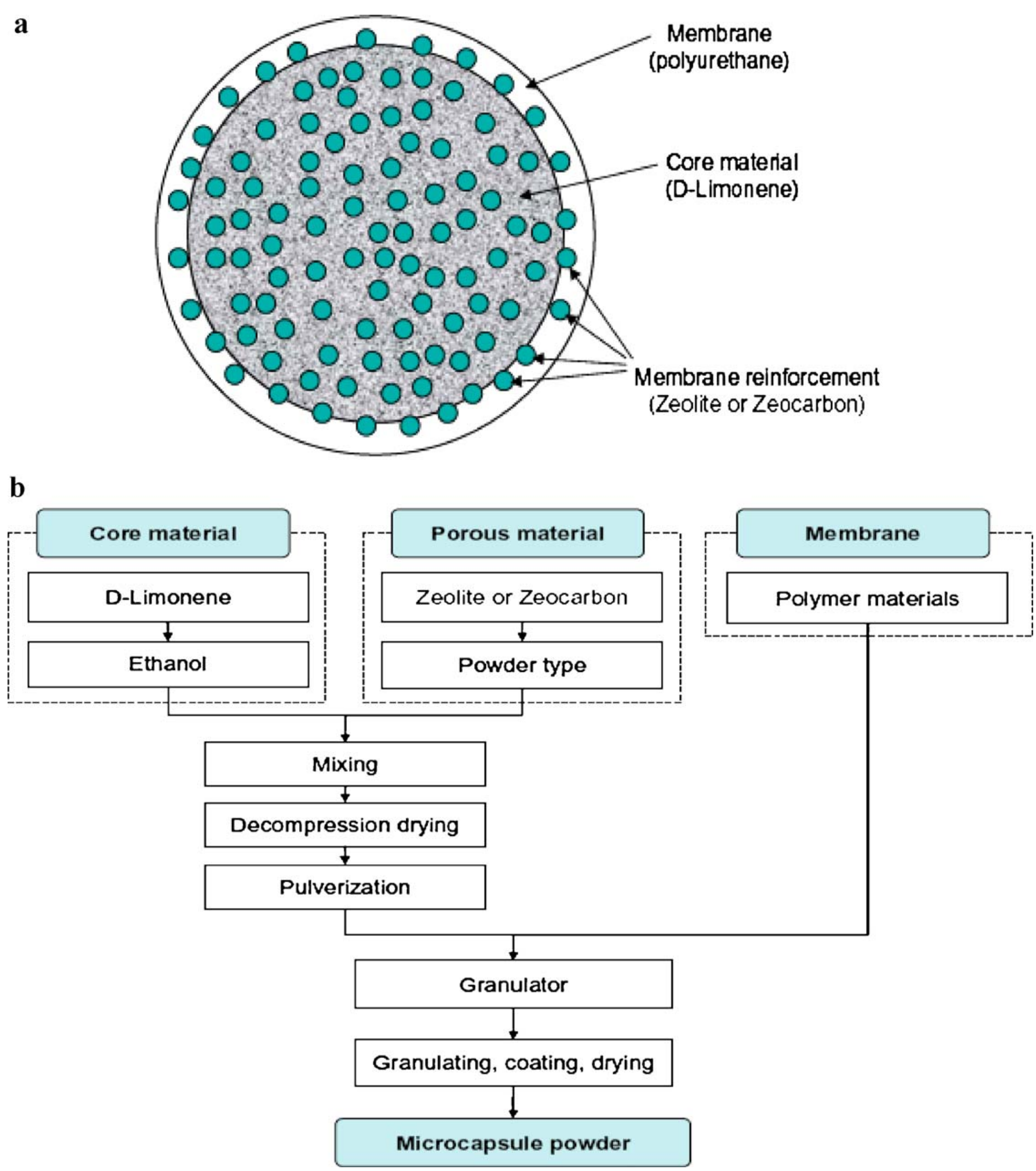

Fig. 10. (a) Composition of anti-fungal microcapsule. (b) Manufacturing process of microcapsule.

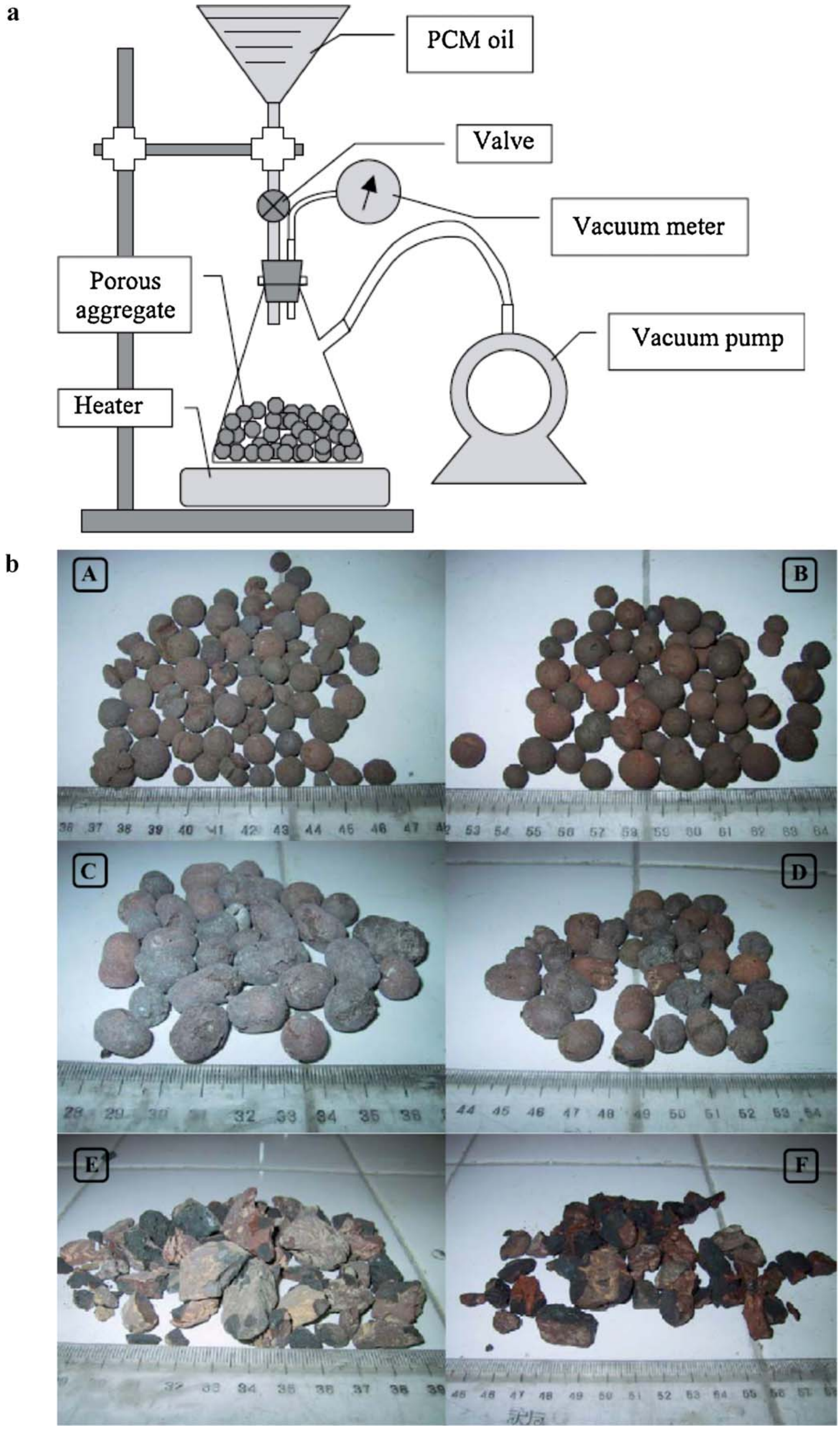

Fig. 11. (a) Schematic drawing of the vacuum impregnation set-up. (b) Porous aggregates before and after absorbing PCM.

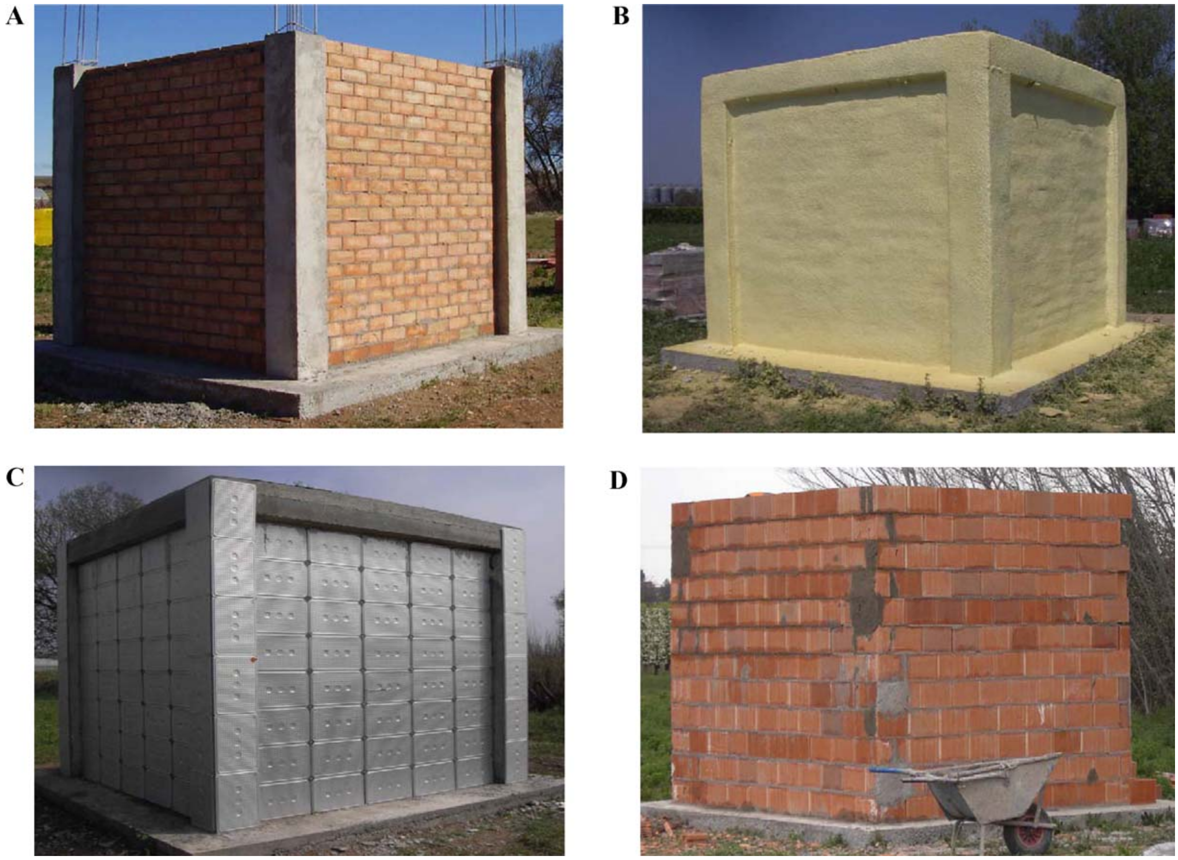

Fig. 12. (a) Brick cubicle. (b) Brick cubicle with polyurethane. (c) Brick cubicle with RT-27 and polyurethane. (d) Alveolar brick cubicles.

storage capacity of a light weight structure. Usually, The PCM is incorporated either in gypsum or in concrete. However, thermal performance of composite highly depends on the microencapsulation process [26]. This review article is focus on PCMs encapsulated system for buildings, i.e. PCM in concrete, PCM gypsum wallboard and microencapsulated phase change material slurry (MPCS).

4.1. PCM encapsulated in concrete

In many areas of the world, concrete is used extensively for residential as well as for commercial buildings construction. In moderate climates, the relatively large thermal mass of the concrete walls can be an advantage, as they store up energy during the day and release it at night, reducing the need for auxiliary cooling/heating. However, the energy storage capacity of concrete can be further modified by the incorporation of phase change materials (PCMs) into the concrete mixture. Park et al. [27] have developed anti-fungal mortar and concrete using microencapsulated biocidal materials. Experimental tests were conducted to verify the applicability and fungal-resistance of mortar and concrete containing these microcapsules. In this study, D-limonene is selected for the core anti-fungal material and Zeolite and Zeocarbon were used for reinforcing the capsule membranes. Zeolite and Zeocarbon have an ability to withstand high friction or impact, which may occur during the mixing and casting process of mortar or concrete. The basic concept of anti-fungal microcapsule is shown in (Fig. 10(a)) and the manufacturing process is described in (Fig. 10(b)). Damage and survival possibilities of microcapsules in the casting stage of mortar and concrete were examined by scanning electron microscopy (SEM) and high pressure liquid chromatography (HPLC).

Lee et al. [28] and Hawes et al. [29] have presented the thermal performance of PCM's in different types of concrete slab blocks. They [28,29] studied and presented the effects of concrete slab alkalinity, temperature, immersion time and PCM dilution on PCM absorption during the impregnation process. Lightweight wood concrete is a mixture of cement, wood chips or saw dust, which should not exceed 15% by weight, water and of the work was to design and construct an experimental installation to study PCMs with a melting temperature between 20 and 25 °C. Zhang et al. [30] have worked on the development of thermal energy storage concrete. In this work, a two-step procedure for incorporation of PCM in building materials was proposed. First, thermal energy storage aggregates (TESAs) were made from porous aggregates and liquid PCM by vacuum impregnation (Fig. 11(a)). Then thermal energy storage concrete (TESC) was produced using TESAs, Portland cement, and other raw materials of normal concrete (Fig. 11(b)) The two-step method made use of the high porosity of porous aggregates to achieve sufficient storage of PCM in concrete, and had the dense cement-based materials surrounding the porous aggregates to avoid the outflow and pollution of PCM. In this study, the

Table 3
Physical properties of macro-encapsulated PCM is added in one cubicle (RT-27 and SP-25 A8).

Property	RT-27	SP-25 A8
Melting point (°C)	28	26
Congealing point (°C)	26	25
Heat storage capacity (kJ/kg)	179	180
Density (kg/L)		
Solid	0.87	1.38
Liquid	0.75	
Specific heat capacity (kJ/kg K)		
Solid	1.8	2.5
Liquid	2.4	
Heat conductivity (W/m K)	0.2	0.6

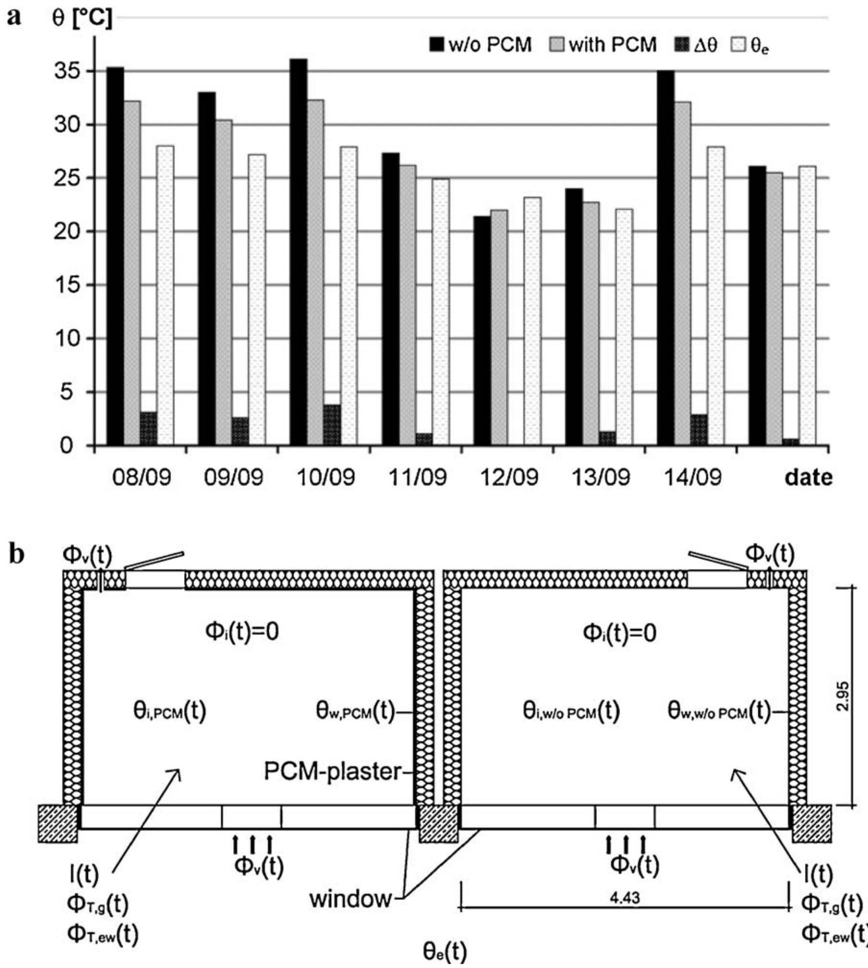

Fig. 13. (a) Comparison of the peak temperatures. (b) Test rooms (on the left with PCM plaster).

feasibility of the two-step method and the effect of the porous structure of the aggregates on their PCM-absorbing capacity and thermal behavior of the TESC have been investigated. Comparison of the thermal energy storage capacity of the concrete with that of a commercially available PCM indicated that TESC has a good potential in the field of building energy conservation application.

Mihashi et al. [31] have used the butyl stearate PCM that melts at around 18 °C on porous lightweight aggregates (LWA) and successfully impregnated. Such a concrete could be used in construction of buildings to maintain interior temperatures near to 18 °C as the melting and solidification of the PCM would delay and, perhaps may avoid the temperature excursions above/below this value. Even when a temperature excursion cannot be avoided, its delay can be extremely beneficial if it the heating/cooling loads towards off peak power consumption, i.e. when power is available at a lower price period.

Bentz and Turpin [32] have worked on the potential applications of phase change materials in concrete technology. They presented three potential applications of PCM-filled lightweight aggregates (LWA) in concrete technology and conclude that phase change materials (PCMs) hold promise in enhancing the performance of concrete technology in several applications, while PCMs may be added directly or in a microencapsulated form to concrete besides, porous lightweight aggregates can also be utilized as the “carrier” for the PCM. For example, an LWA with an absorption capacity of about 20% by mass could provide 350 kg/m^3 of PCM in a typical concrete. As demonstrated for mortars under semi-adiabatic curing conditions, such addition rates could be used to limit the temperature rise and hence, a subsequent rate of temperature decreases of a large concrete section.

Castell et al. [33] presented an experimental set-up to test phase change materials with two typical construction materials (conventional and alveolar brick) for mediterranean construction in real conditions (Fig. 12). Several cubicles were constructed and their thermal performance throughout the time was measured. For each construction material, macro-encapsulated PCM is added in one cubicle (RT-27 and SP-25 A8) (Table 3). The cubicles have a domestic heat pump as a cooling system and the energy consumption is registered to determine the energy savings achieved. They conclude [27] that:

- The experiments under free-floating conditions showed lower peak temperatures (up to 18 °C) and more constant conditions in the cubicles with PCM, smoothing out the daily temperature fluctuations. Some problems with the solidification of the PCM during the night were observed. Therefore, a cooling strategy (either natural or forced) must be defined to improve the performance of the PCM under free-floating conditions. Additional experiments using a heat pump to set and control the inside temperature of the cubicles were performed. The experiments demonstrated that the energy consumption of the cubicles containing PCM has been reduced about 15% compared to that of without PCM. This demonstrates a significant contribution and potential use of PCM in building envelopes for energy savings and thermal comfort in a real house-shaped cubicle.

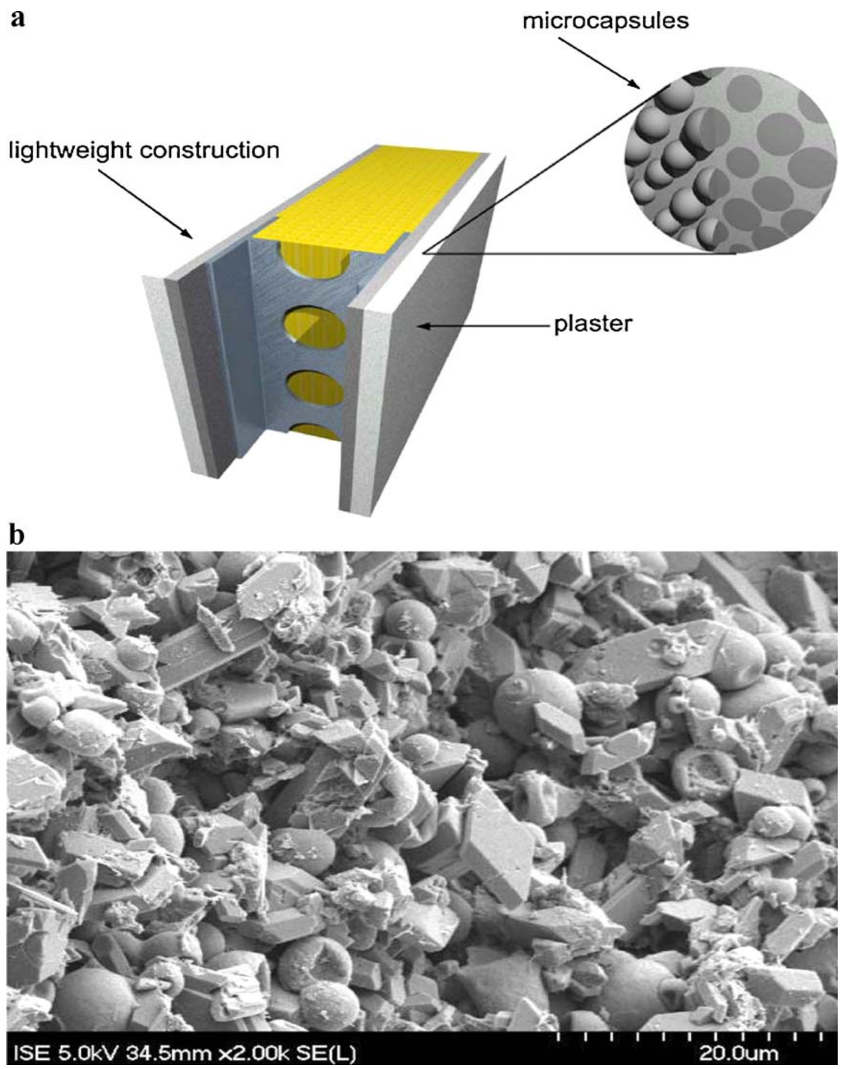

Fig. 14. (a) Schematic view of the PCM microcapsules are integrated into the interior plaster. (b) SEM image of PCM microcapsules in gypsum plaster. The PCM microcapsules with an average diameter of 8 mm are homogeneously dispersed between the gypsum crystals.

- The new results demonstrate the good behavior, energy savings and technical viability of using macro-encapsulated PCM in typical Mediterranean constructive solutions. Moreover, about 1–1.5 kg/year/m^2 of CO_2 emissions could be reduced in the PCM cubicles due to the reduction of power consumption. This reduction can help to mitigate the climate change and the global warming by means of a more efficient and sustainable use of energy.

Voelker et al. [34] have worked for solving the overheating problem in many buildings due to the utilization of lightweight constructions and provide the possible answer to this problem is the emplacement of phase change materials (PCMs), thereby increasing the thermal mass of a building. These materials change their state of aggregation within a defined temperature range. Useful PCMs for buildings shows a phase transition from solid to liquid and vice versa. The thermal mass of the materials is increased by the latent heat. A modified gypsum plaster and a salt mixture were chosen as two materials (using paraffin as well as a salt mixture) for the study of their impact on room temperature reduction. The experiment proved the effect of phase change materials on thermal performance of the building. For example, on 10/9 (Fig. 13(a)) the maximum daily temperature in the test cell without PCM (room 1) was found to be 36.1 °C and in the object with PCM (room 2) was found to be 32.3 °C, which means a significant difference of 3.8 K (Fig. 13(b)). On the other hand, temperatures during the night in room 2 were higher than that of room 1, which is the result of the solidification process of the salt hydrate. A reduction of the peak temperature of up to 4 °C could be ascertained. Furthermore it could be proven that the PCMs forfeit their characteristic heat storage capacity after a few consecutive hot days, if they cannot be discharged over night. Efficient night ventilation can counteract such effects. The influence on the measurement of different parameters

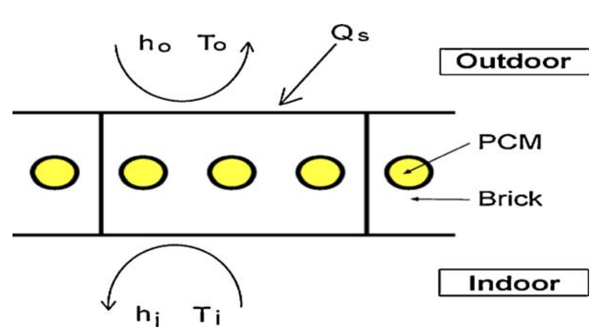

Fig. 15. Schematic representation of the brick–PCM system, and the boundary conditions.

Fig. 16. Sample holder of the thermal mass measuring device (sample placed between two thermo-regulated plates).

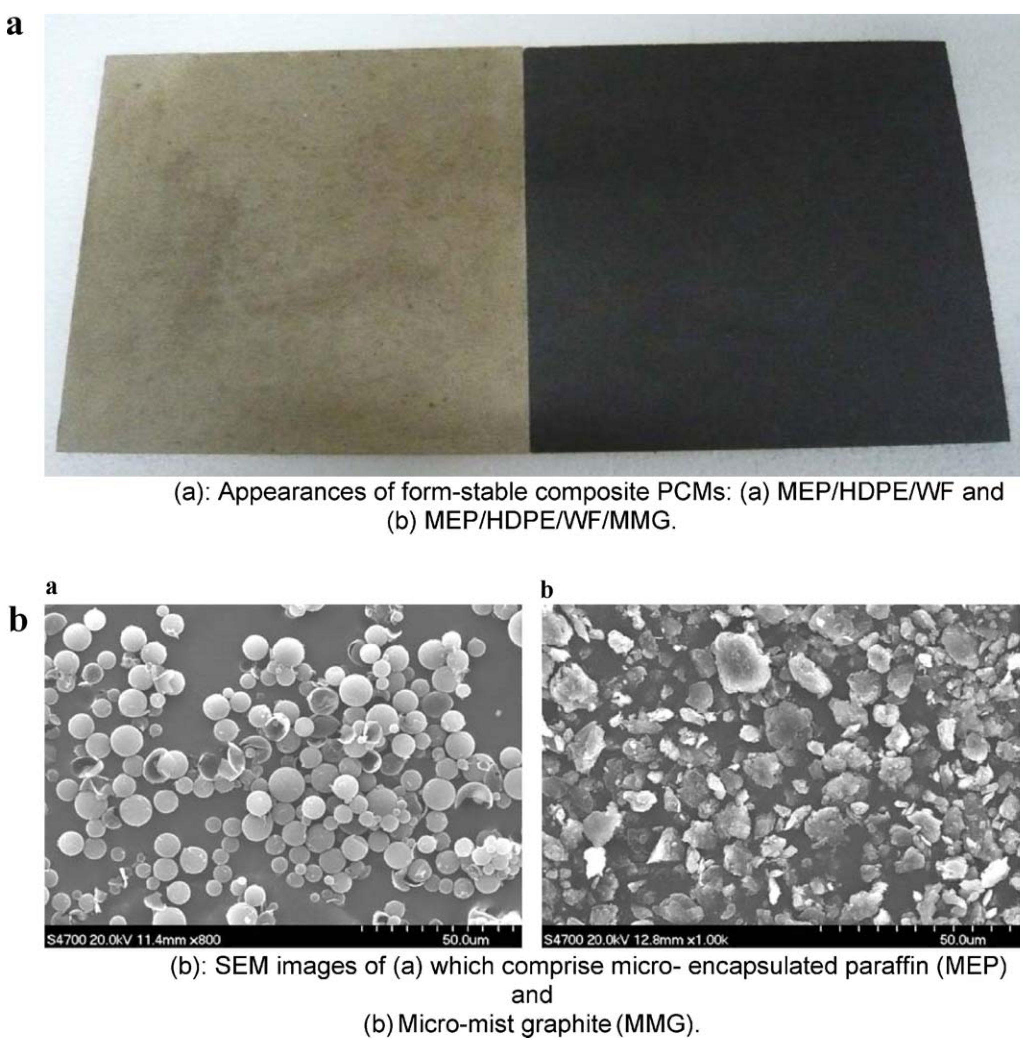

Fig. 17. (a) Appearances of form-stable composite PCMs: (a) MEP/HDPE/WF and (b) MEP/HDPE/WF/MMG. (b) SEM images of (a) which comprise microencapsulated paraffin (MEP) and (b) micro-mist graphite (MMG).

such as the air change rate was varied to simulate the daily routine of an office building. A mathematical model, based on an energy balance equation, was developed to estimate the temperatures in a PCM based air conditioned room.

Schossig et al. [35] worked on the microencapsulation PCM integrate with building materials. Formaldehyde-free microencapsulation of paraffins allows PCM to be readily integrated into conventional construction materials. These capsules, with diameters of only a few micrometers, can be integrated into specially optimized building materials, independent of the phase of the PCM. This solves the problems mentioned above: the capsule shell prevents any interaction between the PCM and the matrix material, there is no extra work at the building site to integrate the PCM products and the capsules are small enough and hence, there is no need to protect them against destruction. The distribution of the small PCM capsules in the wall offers a much larger heat exchange surface, so the heat transfer rate to charge and discharged the stored heat is raised significantly. Fig. 14(a) shows a schematic drawing of this concept, with PCM microcapsules integrated into plaster, and Fig. 14(b) shows a scanning electron microscope (SEM) image of these capsules in gypsum plaster.

Alawadhi [36] presented the thermal analysis of a building brick containing phase change material (PCM) to be used in hot climates. The objective of using PCM was to utilize its high latent heat of fusion to reduce the heat gain by absorbing the heat in the bricks through the melting process before it reaches the indoor space. The considered model consists of bricks with cylindrical holes filled with PCM (Fig. 15). The problem was solved in a two-dimensional space using the finite element method. The thermal effectiveness of the proposed brick–PCM system was evaluated by comparing the heat flux at the indoor surface to a wall without the PCM during typical working hours. A paramedic study has been conducted to assess the effect of different design parameters, such as the quantity of PCM's, type, and location of PCM in the brick. The results indicated that the heat gain has been significantly reduced when the PCM was incorporated into the brick, and increasing the quantity of the PCM has a positive effect besides, the PCM cylinders located at the centerline of the bricks show the best performance.

Hunger et al. [37] presented a set of experiments using different amounts of PCM in self-compacting concrete mixes. The study focused on the direct mixing of microencapsulated PCM with concrete and its influence on the material properties (Fig. 16). Therefore, the fresh concrete properties and the hardened properties were investigated; the hardened properties comprise strength tests and a thorough assessment of the thermal properties. The modeling and experiments involving hydration showed that the

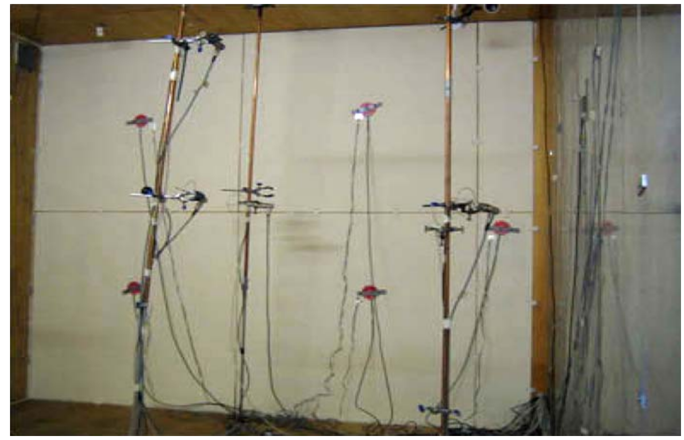

Fig. 18. Image of PCM wall.

temperature peak of hydration could be reduced up to 28.1% by increasing the PCM content to 5%. However, the heating rate cannot be changed by the PCM, only the absolute temperature peak is lowered by the amount of energy stored temporarily in the PCM. The emission of heat from the sample therefore, continued for a longer time when the PCM content was higher. On the other hand, the result of experiment has shown that the increasing amount of PCM leads to a lower thermal conductivity and an increased heat capacity, and both significantly improve the thermal performance of concrete and therefore save energy.

Li et al. [38] worked on microencapsulated paraffin/high-density polyethylene/wood flour composite to form-stable phase change material. Six novel polymer-based form-stable composite phase change materials (PCMs), comprised with microencapsulated paraffin (MEP) as latent heat storage, medium and high-density polyethylene (HDPE)/wood flour compound as supporting material, were prepared by blending and compression molding method for potential use in the latent heat thermal energy storage (LHTES) applications (Fig. 17(a)). Micro-mist graphite (MMG) was added to improve thermal conductivities. The scanning electron microscope (SEM) images revealed that the form-stable PCMs have homogeneous constitution and most of MEP particles in them were undamaged (Fig. 17(b)). Both the shell of MEP and the matrix prevent molten paraffin from leakage. Therefore, the composite PCMs are described as form-stable PCMs. The differential scanning calorimeter (DSC) results showed that the melting and freezing temperatures as well as the latent heats of the

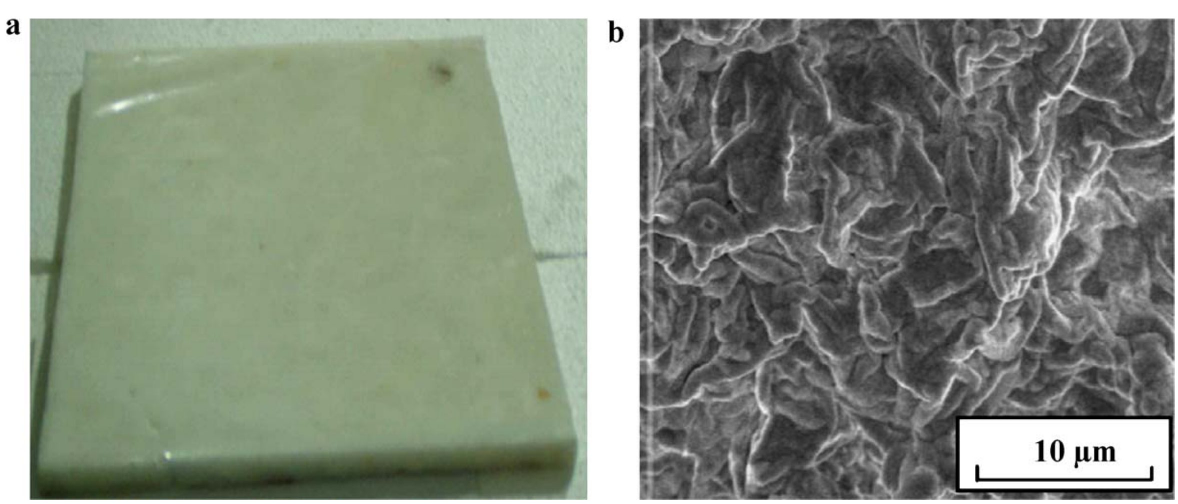

Fig. 19. The photos of the shape-stabilized PCM: (a) photo of the PCM plate; (b) electronic microscopic picture by scanning electric microscope (SEM).

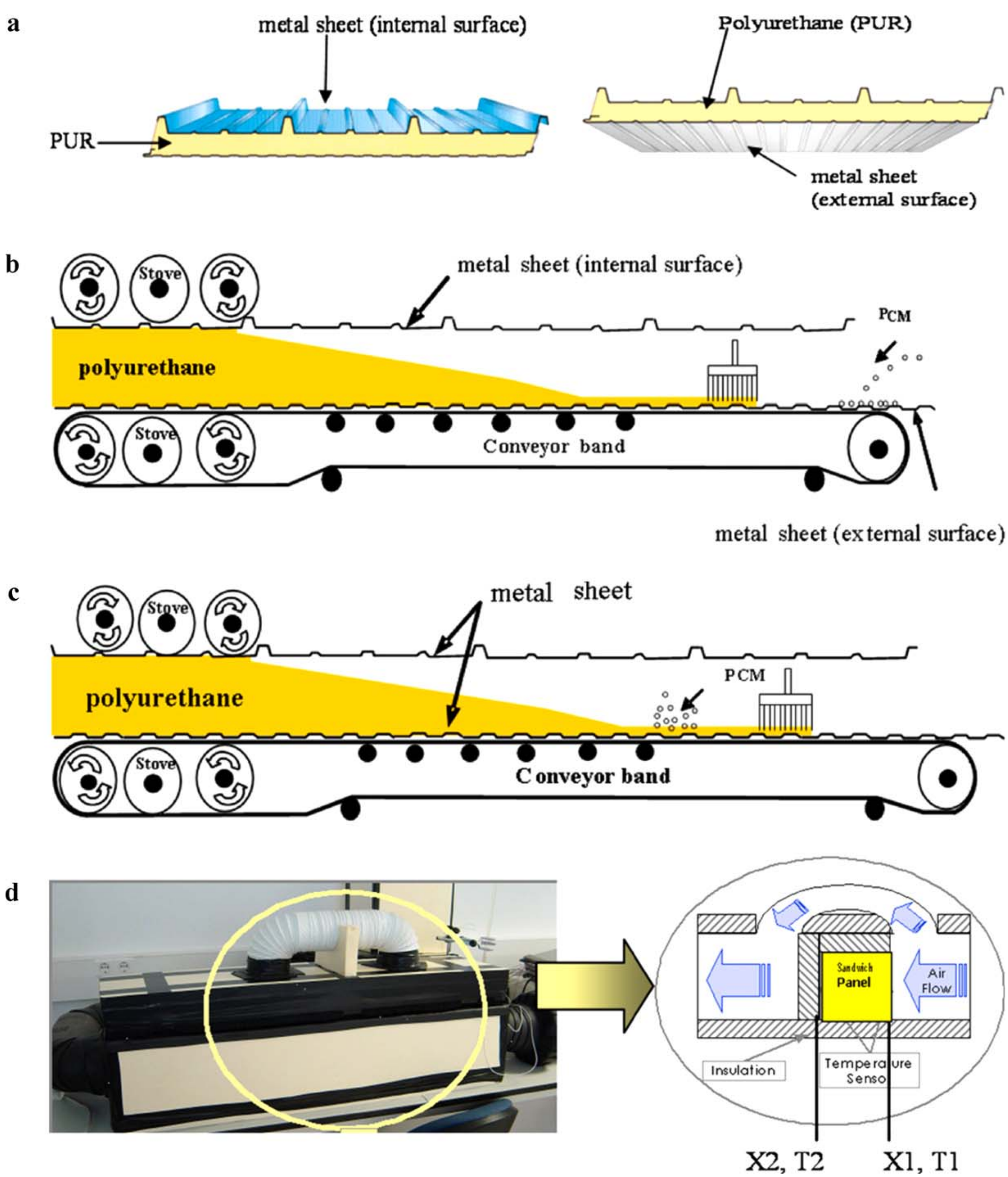

Fig. 20. (a) View of the sandwich panel. (b) Manufacture of the sandwich panel with PCM (case 2). (d) Experimental installation to measure the temperature evolution in a solid sample (University of Zaragoza).

prepared form-stable PCMs are suitable for potential LHTES applications. The thermal cycling test indicated the form-stable PCMs have good thermal stability, although it was subjected to 100 melt–freeze cycles. The thermal conductivity of the form-stable PCM was increased by 17.7% by adding 8.8 wt.% MMG. The results of mechanical property test indicated that the addition of MMG has no negative influence on the mechanical properties of form-stable composite PCMs. Taking one with another, these novel form-stable PCMs have the potential for LHTES applications in terms of their proper phase change temperatures, improved thermal conductivities, outstanding leak tightness of molten paraffin and good mechanical properties.

4.2. PCM encapsulated in wall/wallboard

Wallboards are cheap and widely used in building applications, which makes them very suitable for the application of PCMs. Wallboards enhanced with PCMs will provide thermal storage distributed throughout the complete building, enabling passive solar design and off-peak cooling in traditional frame constructions with a typical low thermal mass. The performance of the PCM enhanced wallboards will depend on several factors: the melt temperature of the PCM, the temperature range over which melting occurs, the latent heat capacity per unit area of the wall, how the PCMs are incorporated in the wallboard, climatic conditions, direct solar

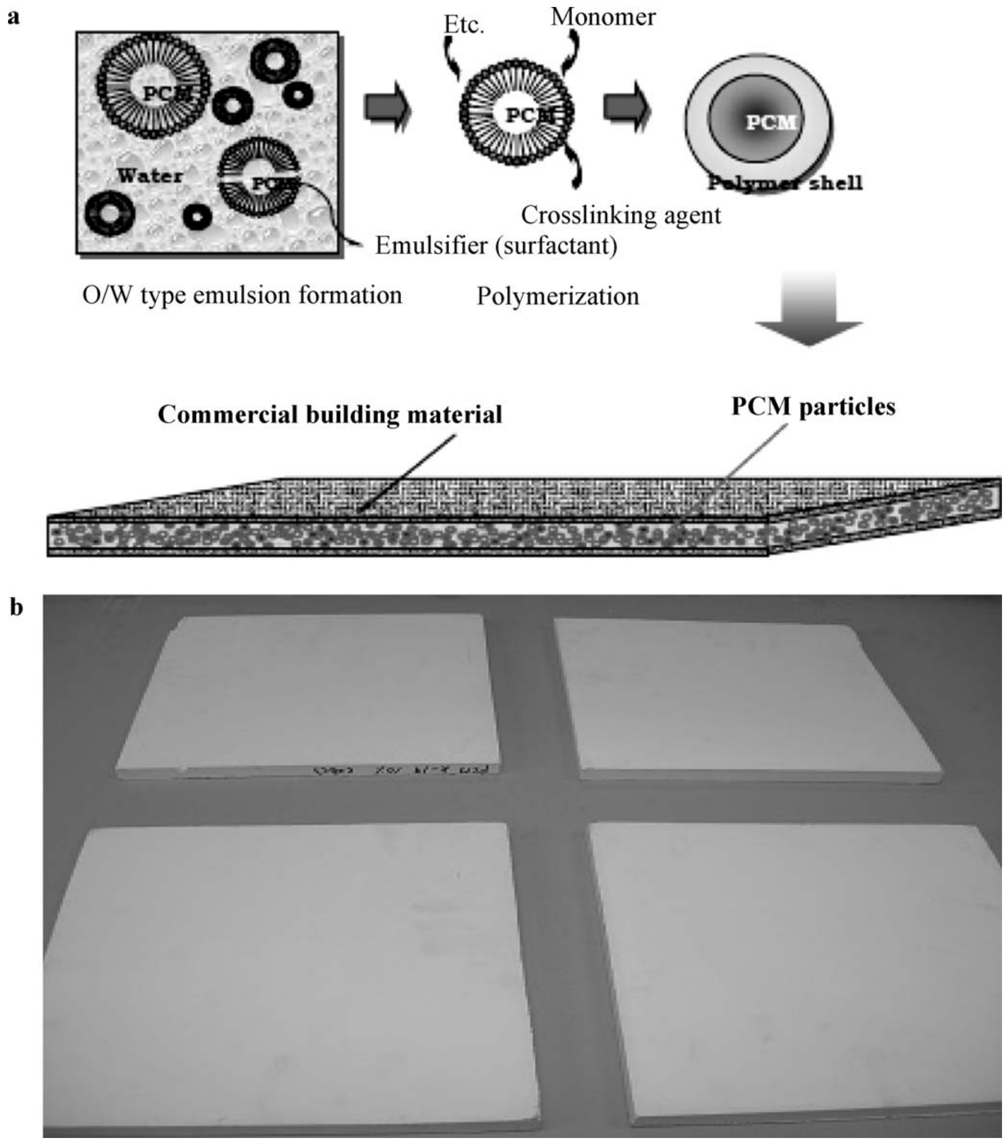

Fig. 21. (a) Concept diagram of building materials containing Micro-PCM. (b) Photograph of PCM gypsum wallboards.

gains, etc. However, because all factors cannot be taken into account in each case, most studies on PCM enhanced wallboards deal with the choice of the phase change material, the manufacturing methods and the method of testing.

Liu and Awbi [39] studied the performance of phase change material boards under natural convection. In this work, the thermal performance of an environmental chamber fitted with phase change material boards was investigated (Fig. 18). During a full-cycle experiment, i.e. charging–discharging cycle, the PCM boards on a wall can reduce the interior wall surface temperature during the charging process, whereas the PCM wall surface temperature is found to be higher than that of the other walls during the heat releasing process. It is found that the heat flux density of the PCM wall in the melting zone is almost twice than that of ordinary wall. Also, the heat-insulation performance of a PCM wall is better than that of an ordinary wall during the charging process, while during the discharging process; the PCM wall releases more heat energy. The convective heat transfer coefficient of PCM wall surface calculated using equations for a normal wall material produces an underestimation of this coefficient. The high convective heat transfer coefficient for a PCM wall is due to the increased energy exchange between the wall and the indoor air.

Zhou et al. [40] have developed the shape stabilized PCM plates and thermal performance of two phase change material composites, mixed type PCM-gypsum and shape stabilized PCM plates (Fig. 19), has been numerically evaluated in a passive solar building in Beijing (China) with an enthalpy model. The results showed that: (1) for the given operating conditions, the optimal melting temperature is about 21 °C; (2) PCM composites with a narrow phase transition zone provide better thermal performance; (3) both mixed type PCM–gypsum and shape-stabilized PCM plates effectively shave the indoor temperature swing by 46% and 56%, respectively; (4) the shape-stabilized phase change material (SSPCM) plates respond more rapidly than the mixed type PCM gypsum and prove to be thermally more effective in terms of utilizing the latent heat.

Castellón et al. [41] focused on microencapsulated phase change material in sandwich panels. The goal of this study was to demonstrate the feasibility of using the microencapsulated PCM (Micronal BASF) in sandwich panels to increase their thermal inertia and to

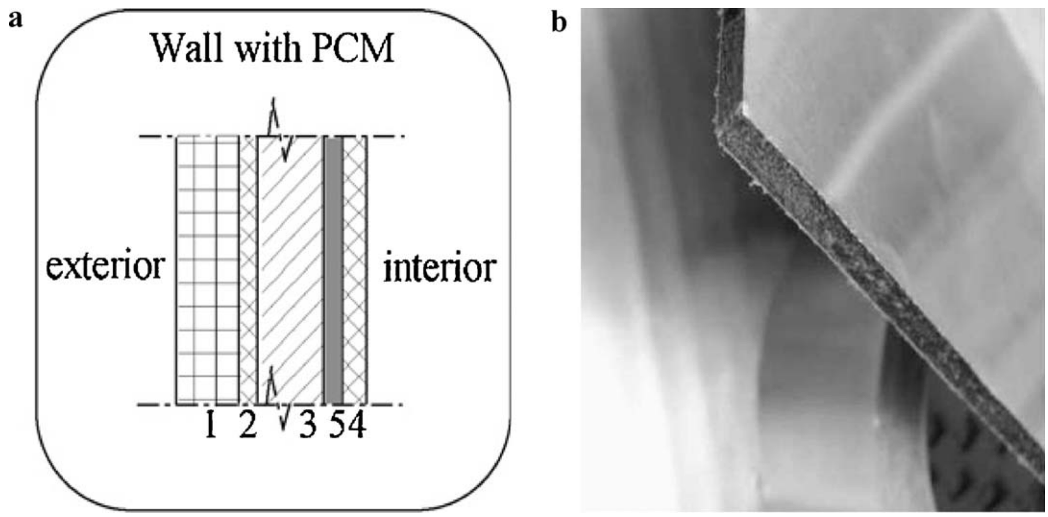

Fig. 22. (a) Walls compositions with PCM material. (1) 50 mm wood plate, (2) 10 mm plaster, (3) 50 mm polystyrene, (4) 13 mm plaster and (5) 5 mm PCM. (b) PCM wall board (Dupont de Nemours material)

reduce the energy demand of the final buildings. In this work, in manufacturing the sandwich panel with microencapsulated PCM three different methods were tested (Fig. 20(a)–(d)). In case 1, the PCM was added mixing the microencapsulated PCM with one of the components of the polyurethane. In the other two cases, the PCM was added either a step before (case 2) or a step after (case 3) the addition of the polyurethane into the metal sheets. The results show that in case 1 the effect of PCM was overlapped by a possible increase in thermal conductivity, but an increase of thermal inertia was found in case 3. In case 2, different results were obtained due to the poor distribution of the PCM. Some samples showed the effect of the PCM (higher thermal inertia), and other samples results were similar to the conventional sandwich panel. In both the cases (2 and 3), it is required to industrialize the process to improve the results.

Lee et al. [42] have developed the microencapsulated phase change material for building materials. Micro-PCM was prepared using in situ polymerization for PCM building materials (Fig. 21(a) and (b)). The average particle size of Micro-PCM was between 5 and 20 μm. As the concentration of emulsifier is increased, the mean particle size shows a minimum value at 4–5 wt.% at 9000 rpm and changes differently with the emulsification speed. Also, the agglomeration or break of the particle size shows a minimum value of 4–5 wt.% at 9000 rpm and changes differently with the emulsification speed. Also the agglomeration or break off the microcapsule occurs at below 2 wt.% of emulsifier concentration; therefore low concentration of emulsifier causes difficulty of encapsulation. The latent heat of Micro-PCM samples was found to be 210 J/g (23 °C), 200 J/g (24 °C) and 150 J/g (28 °C) with the core materials, respectively. The thermal conductivity of the gypsum wallboard without PCM is found to be 0.144 W/m K, but that of the PCM gypsum wallboard is found to be somewhere between 0.128 and 0.163 W/m K. They [36] also concluded that, as the thickness of PCM olefin film increases, the capacity of thermal storage inside chamber also increases.

Rozanna et al. [43] studied on the thermal characteristics of phase change material (PCM) in gypsum board for building applications. The eutectic mixture of lauric–stearic acids (75.5:24.5, w/w) a melting point of 34.1 °C, heat of fusion of 171.1 J/g has been used in wall board. When impregnated in gypsum boards, the thermal characteristics of the mixture were found to be unchanged practically, with one sharp peak and no additional peak or hump. Indeed, the immersion did not affect the physical characteristics of the gypsum boards. It is recommended that a suitable insulator be attached to the PCM-gypsum board and an accelerated thermal cycle test run is needed to detect any change in the thermal behavior after long-term use.

Kuznik and Virgone [44] experimentally worked on phase change material wallboard for building use. The thermal performance of a PCM copolymer composite wallboard was experimentally investigated in a full scale test room. The test cell is totally controlled so that at a typical day the temperature and solar radiative flux can be repeated. This is one of the rare studies allowing a differential analysis of walls with and without PCM material, under controlled thermal and radiative effects. The tests concern the behavior of the test cell for summer, mid-season and winter cases, for all seasons inclusion of the PCM wallboard reduces the air temperature fluctuations in the room. The decrement factor observed for the cases with PCM wallboard and with regular wall is about 0:7 for all the season tested (Fig. 22(a) and (b)). The wall surface temperature fluctuations are also reduced. Finally they concluded that, the PCM composite is interesting to enhance the human thermal comfort for building applications, mainly due to three reasons:

- The PCM material included in the walls strongly reduces the overheating effect and the energy stored is released to the air room when the temperature is the minimum.
- The wall surface temperature is lower when using PCM wallboard, then the thermal comfort is enhanced by radiative heat transfer.
- The natural convection mixing of the air is also enhanced by PCM material, avoiding uncomfortable thermal stratifications.

Shilei et al. [45] applied of eutectic mixtures of capric acid (CA) and lauric acid (LA) in building wallboards for heat energy storage. The phase transition temperature and values of latent heat of eutectic mixtures of CA and LA are found to be suitable for incorporation with the building materials to form phase change wallboards being used for thermal energy storage. Besides, 120, 240 and 360 accelerated thermal cycle tests were conducted to study the changes in latent heat of fusion and melting temperature of phase change wallboards combined with the eutectic mixtures of CA and LA. Differential scanning calorimetry (DSC) tested the transition temperature and latent heat. The results showed that the melting temperature and latent heat of these phase change wallboards with eutectic mixtures have not obvious variations after repeated 360 thermal cycles, which proved that these PCM wallboards have good thermal stability for melting temperature and

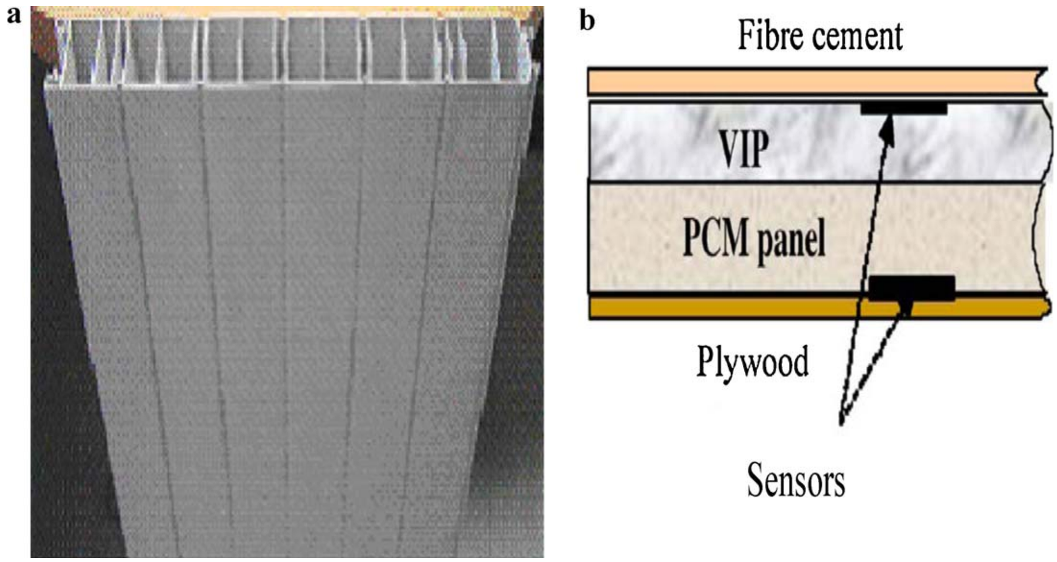

Fig. 23. (a) View of a PVC panel. (b) Location of sensors of flux/temperature on the panels with PCM.

latent heat of fusion for long time application. Therefore, they can be used for latent heat storage in the field of building energy conservation.

Ahmad et al. [46] tested a prototype cell using light wallboards coupling vacuum isolation panels and phase change material. A solution to increase this inertia is to incorporate a phase change material (PCM) in this envelope. The performance of a test-cell with a new structure of light wallboards containing PCMs submitted to climatic variation and a comparison is made with a test-cell without PCMs. To improve the wallboard efficiency a vacuum insulation panel (VIP) was associated to the PCM panel (Fig. 23(a) and (b)). This new structure allows the apparent heat capacity of the building to be increased, the solar energy transmitted by windows to be stored without raising the indoor cell temperature, and the thickness of the wallboard to be decreased compared with that of traditional wallboards. An experimental study was carried out by measuring temperature and heat fluxes on and through the wallboards. The indoor temperature, which has a special importance for occupants, was also measured. A numerical simulation with the TRNSYS software was carried out by adding a new module representing the new wallboard, which showed a good agreement with experimental results. It was concluded that this new tool will allow users to simulate the thermal behavior of buildings with PCMs walls.

Borreguero et al. [47] have studied the feasibility of incorporating microcapsules containing phase change materials (PCMs), in gypsum wallboards to increase the wall energy storage capacity by a suspension polymerization process. First, the energy storage capacity of the resulting microcapsules and the microencapsulation efficiency was maximized by studying the influence of the synthesis variable core/coating mass ratio on the suspension polymerization process. Results indicate that the higher paraffin wax to styrene monomer mass ratio, the lower is the efficiency of the microencapsulation. A mass ratio of Rubitherm RT27 to styrene monomer equal 1.5 allowed obtaining microcapsules with the highest energy storage capacity and better microencapsulation efficiency. It was also observed that the energy storage capacity is dependent on the particle size; the maximum capacity was obtained for a particle size of 500 μm. Finally, the thermal behavior of three gypsum wallboards one without PCMs and the others doped with 4.7% and 7.5% by weight of microcapsules containing Rubitherm RT27 at the optimal core/coating mass ratio was studied.

5. Conclusions

Microencapsulation is a knowledge-intensive technology with a rapid growth in real life building applications. Through the research literature, microencapsulation applications are found to be very useful technology into the field of building construction materials. Nowadays, microencapsulated phase change materials are widely used in building materials viz. PCM in concrete, PCM gypsum wallboard and microencapsulated phase change material slurry, etc. The following conclusions can be drawn from the microencapsulated phase change materials for building applications:

- The fastest growing segments of microencapsulated in construction materials are organic latent heat storage materials because of high energy storage capacity with low super-cooling and good mixing property with construction materials.
- Different methods are being used for microcapsulation but in situ polymerization method is found to be popular among them.
- Lightweight buildings are facing temperature fluctuation problem in many countries. Microencapsulation widely used to integrate PCMs in wallboard and hence, the wallboard with PCM is showing promising result for temperature fluctuation, heat/cool storage device to provide the possible answer to this problem with existing and future buildings.
- Microencapsulation technology has good potential and is also being used in some other applications such as textiles, pharmaceutical, medical applications, food industry, chemical industries, and electronics.

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